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COMPLETE SPECIFICATION

(See Section 10 and Rule 13)

Title of the Invention

**A NOVEL GRASPING AND PRELOADING MECHANISM FOR GRASPING
NON-COOPERATIVE SPACECRAFTS**

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Preamble to the Description

**The following specification particularly describes the invention and the
manner in which it is to be performed.**

FIELD OF INVENTION

[0001] The present invention relates to On-Orbit Servicing (OOS), specifically a servicer spacecraft with capabilities of grasping non-cooperative target to increase the life of existing spacecrafts in Geostationary Equatorial Orbit (GEO) and Low Earth orbit (LEO).
5

BACKGROUND OF INVENTION

[0002] On-Orbit Servicing (OOS) refers to the practice of maintaining, repairing, upgrading, and repositioning spacecraft directly in space, which significantly extends their operational life and functionality. By using advanced robotics and autonomous
10 systems, OOS allows for tasks like refueling, fixing issues, and updating technology without the need for launching new spacecrafts. Additionally, OOS can provide life extension to aging, non-cooperative spacecraft that were not originally designed for servicing, by using specially equipped servicer spacecrafts to dock and perform necessary maintenance or adjustments. This not only saves costs but also reduces space
15 debris, making space operations more sustainable. With successful missions already demonstrating its potential, OOS is becoming an essential capability for both government and commercial space missions, ensuring spacecrafts continue to support communication, navigation, and scientific endeavors efficiently.

[0003] The technology currently available to carry out a successful OOS mission for
20 an existing non-cooperative spacecraft (client spacecraft) in LEO or GEO involves either grasping the client spacecraft through the Liquid Apogee Motor (LAM) throat or grasping Launch Adapter Ring (LAR) of the client spacecraft using robotic arm.

[0004] In the LAM throat grasping method, the client spacecraft is grasped by inserting a probe, mounted on the servicer spacecraft, into the LAM at the aft end of the client
25 spacecraft. The liquid apogee engine guides the probe, which gradually moves through the engine's throat to grasp the client spacecraft. The probe then retracts, pulling stanchions against the interface ring to lock and preload the two spacecrafts together.

[0005] The prior art "MEV-1 with Intelsat 901 & MEV-2 with Intelsat 10-02" features both a grasping mechanism and a docking mechanism on the servicer spacecraft. The grasping mechanism includes a ball-screw actuated sliding stage and an eddy current damper with a rack and pinion assembly, which actuates a compliant probe with spring-loaded fingers. This probe is inserted into the LAM of the client spacecraft during the approach motion. The docking mechanism incorporates abutment pads/rigid stanchions that interface with the launcher interface ring of the client spacecraft. When preload is applied to these pads/stanchions through the probe retraction, the docking mechanism maintains a rigid docked interface under loads induced by thrusting maneuvers of the combined spacecraft or by on-orbit servicing operations, as shown in Figure 1.

[0006] In the robotic arm grasping method, the client spacecraft is grasped by gripping the adapter ring with specialized grippers mounted on the servicer spacecraft's robotic arm. The grippers on the robotic arm gradually approach the client spacecraft and softly grasp the adapter ring. The robotic arm then actuates, pulling stanchions against the interface ring to lock and preload the two spacecraft together.

[0007] The prior art, "European Space Agency (ESA) – Grasp Tool," demonstrates the capability of the servicer spacecraft to perform rendezvous, grasping, berthing, and manipulating of a client satellite provisioned for servicing operations, including refueling and payload transfer or replacement. ESA's grasp tool is designed to grasp the Launch Adapter Ring (LAR). It consists of two sets of jaws with adjustable angles to fit different diameters. Both jaws contain contactless 'trigger' sensors for detecting the target object within the grasp envelope, as well as for determining the success or failure of a grasp attempt. The tool operates in two main stages, utilizing two separate mechanisms. The first mechanism performs a fast-acting soft grasp by quickly closing the jaws over the target object when the sensors on the jaws are triggered. The key idea of this mechanism is to prevent the target object from escaping the grasp envelope. The jaws are held together using a solenoid and driven by a DC motor. Once the jaws have

closed, the second mechanism pulls the target onto rigidization surfaces until the desired preload is reached, ensuring a firm grasp. The LAR gripper is secured against launch loads using a clamp band system. When a pre-defined gripping force is achieved, the motor stops, and gripping is finalized by activating a motor brake. Figure 2 illustrates the overall concept of ESA's grasp tool gripper mechanism and the LAR gripper hardware.

[0008] However, none of the prior art discloses features such as integrated robotic arms and stanchion grippers capable of grasping, preloading, and releasing the client spacecraft repeatedly as per requirement. Additionally, they do not address the capability to capture interface rings of both GEO (1194 mm LAR) and LEO (937 mm LAR) type spacecraft. Furthermore, the prior art has several potential drawbacks, including:

- The jaws/fingers of the prior-art LAR gripper are held together using the solenoid and the gripper is held against launch loads using a clamp band system.
- The prior-art systems have a total mass of approximately 15 kg and a grasp misalignment capability of ± 22 mm and $\pm 2.4^\circ$ across all axes.
- The use of an additional hold-down system increases mass and launch costs, while also reducing the overall system's reliability due to the presence of extra moving components.

[0009] The proposed Grasping and Preloading Mechanism (GPM) is an advanced technology demonstrator designed to extend the life of existing spacecraft like GSAT-8. It integrates both grasping and preloading functions into a compact system, capable of handling both GEO (1194 mm LAR) and LEO (937 mm LAR) spacecraft interface rings. With a lightweight design under 2 kg, the GPM offers high precision with misalignment capabilities of ± 20 mm and $\pm 5^\circ$ across all axes and can handle client spacecraft weighing up to 1.5 tons. Its compact gripper reduces overall system mass

and complexity, making it suitable for various applications, including refueling defunct spacecrafts and performing berthing operations on the Indian Space Station.

OBJECT OF INVENTION

[0010] Some of the objects of the present disclosure, which at least one embodiment
5 herein satisfies, are as follows:

[0011] An object of the present disclosure is to develop a novel Grasping and Preloading Mechanism (GPM) for Indian On-Orbit Servicing (OOS) of existing non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space.

10 [0012] Another object of the present invention is that the proposed GPM mechanism has the ability to grasp both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings.

[0013] Yet another object of the present invention is to design the grasp fingers so that they are held down during launch by an ingenious wedge-type stopper and released
15 once in orbit to perform the necessary operations efficiently.

[0014] Yet another object of the present invention is to develop a mechanism that can perform both grasping and release functions using a single actuator.

[0015] Yet another object of the present invention is to avoid the need for a dedicated hold-down system by employing an ingenious wedge-type stopper, thereby reducing
20 mass, launch costs, and enhancing overall system reliability.

[0016] Yet another object of the present invention is that the proposed GPM mechanism features a lightweight design under 2 kg, offering high precision with misalignment capabilities of ± 20 mm and $\pm 5^\circ$ across all axes, and can handle client spacecraft weighing up to 1.5 tons.

[0017] Yet another object of the present invention is to develop a closed-loop system that achieves safe-distance grasping and the desired preload between spacecraft, monitored via a force-based cutoff sensor and mechanism entry sensors.

[0018] Other objects and advantages of the present disclosure will be more apparent from the following description, which is not intended to limit the scope of the present disclosure.

SUMMARY OF THE INVENTION

[0019] For on-orbit servicing (OOS) missions, advanced technology is needed to enable servicer spacecraft to grasp non-cooperative targets, thereby extending the operational life of existing spacecraft in GEO and LEO. The primary goal is to extend the life of aging, non-cooperative spacecraft while maintaining their payload services. A servicer spacecraft, equipped with this grasping technology, approaches the end-of-life client spacecraft at low velocity, using closed-loop guidance and proximity sensors to ensure precise and safe grasping.

[0020] The present invention introduces a novel Grasping and Preloading Mechanism (GPM) for the autonomous capture of non-cooperative spacecraft. This mechanism is capable of grasping the launch adapter ring of the client spacecraft, enabling a servicer spacecraft to engage with a client spacecraft that has no specialized docking features. The servicer spacecraft, equipped with this mechanism, has the ability to autonomously capture, preload, and release various types of existing client spacecraft multiple times for life extension. The GPM comprises a robotic arm that is actuated to grasp the LAR of the client spacecraft and pull it towards the preloading surface of the servicer spacecraft. Additionally, the GPM includes a gripper mechanism equipped with grasp fingers and preload fingers, which instantaneously grasp the LAR and arrest all degrees of freedom (DOF) of the client spacecraft. The GPM also features a preload mechanism with two stanchion grippers mounted at 120° angles to each other and 120° to the robotic arm gripper, ensuring balanced grasping around the LAR and achieving the

predefined preload between the spacecraft. The mechanism is also configured to release and separate the two-spacecraft using an ingenious wedge-type stopper and is capable of repeating these operations multiple times if required.

[0021] The method for the autonomous grasping of non-cooperative spacecraft using the GPM involves several key steps. When the deck camera mounted on the robotic arm gripper and the Mechanism Entry Sensor (MES) on the servicer spacecraft detect that the two spacecraft are within the safe grasping zone, the robotic arm with the gripper mechanism is actuated to softly grasp the LAR of the client spacecraft. Initially, the grasp fingers in the gripper mechanism are actuated to securely grasp the LAR, while the preload fingers provide self-alignment and arrest all degrees of freedom (DOF) of the client spacecraft. The robotic arm is then actuated to pull the client spacecraft towards the preload surface of the servicer spacecraft. Stanchion grippers on the preload surface apply the predefined preload between the spacecraft using an ingenious wedge-type stopper. This preload is monitored by a force sensor mounted on the stanchions, which is prepositioned to actuate at the desired preload. Once the final preload is achieved, the stanchion grippers and robotic arm gripper are separated by 120° each around the LAR, ensuring balanced grasping, and the On-Orbit Servicing (OOS) operations are initiated. After completing the OOS operations, the grippers are actuated to push the client spacecraft away from the servicer spacecraft, eliminating the need for a separate release mechanism. Thus, the GPM can autonomously grasp, preload, and release the client spacecraft repeatedly as required.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

[0022] The other objects, features and advantages will occur to those skilled in the art from the following description of the preferred embodiment and the accompanying drawings in which:

[0023] **Figure 1** is a conceptual illustration of the grasp concept of MEV-1 with Intelsat 09, according to an embodiment of the existing prior-art.

[0024] **Figure 2** is a schematic representation of overall concept of ESA's grasp tool gripper mechanism and the LAR gripper hardware, according to an embodiment of the existing prior-art.

[0025] **Figure 3** is a schematic representation of the overall configuration of novel
5 Grasping and Preloading Mechanism (GPM), according to an embodiment of the present invention.

[0026] **Figure 4** is a schematic representation of the major mechanisms involved in the GPM, according to an embodiment of the present invention.

[0027] **Figure 5** is a schematic representation of the GPM concept, demonstrating its
10 ability to grasp both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings, according to an embodiment of the present invention.

[0028] **Figure 6** is a schematic representation of the robotic arm attached with gripper mechanism, according to an embodiment of the present invention.

[0029] **Figure 7** is a pictorial representation of the hardware elements of the robotic
15 arm equipped with the gripper mechanism, according to an embodiment of the present invention.

[0030] **Figure 8** is a schematic representation of the gripper mechanism, according to an embodiment of the present invention.

[0031] **Figure 9** is a pictorial representation of the hardware elements of the gripper
20 mechanism, according to an embodiment of the present invention.

[0032] **Figure 10** is a schematic representation of the preloading mechanism, according to an embodiment of the present invention.

[0033] **Figure 11** is a pictorial representation of the lab level testing of GPM prototype, according to an embodiment of the present invention.

[0034] **Figure 12** is a pictorial representation of the lab level testing of GPM hardware, according to an embodiment of the present invention.

[0035] **Figure 13** is a conceptual illustration of the various phases involved in the method for the autonomous grasping of non-cooperative spacecraft using the GPM,
5 according to an embodiment of the present invention.

LIST OF REFERENCE NUMERALS

- 100 – Grasping and preloading mechanism
- 101 – Servicer spacecraft
- 102 – Client spacecraft
- 10 103 – Deck camera
- 104 – MES sensors
- 105 – LAR
- 105A – 1194mm LAR
- 105B – 937mm LAR
- 15 120 – Robotic arm
- 121 – Arm-I
- 122 – Arm-II
- 123 – Shoulder joint
- 124 – Elbow joint
- 20 125 – Gripper camera
- 126 – Servicer spacecraft interface
- 140 – Gripper mechanism
- 141 – Grasp fingers
- 142 – Preload finger
- 25 143 – Compression spring
- 144 – Finger housing
- 145 – Gripper housing

- 146 – Grasp motor
- 147 – Preload motor
- 148 – Arm interface
- 149 – Gripper joints
- 5 150 – Contact switch
- 160 – Preloading mechanism
- 161 – Stanchions
- 162 – Stanchion grippers
- 163 – Wedge type stopper
- 10 164 – Force sensor

DETAILED DESCRIPTION OF THE INVENTION

[0036] The present invention may be embodied in several forms, and the details of embodiments of the present invention will be described in the following content with figures. The embodiments described below with reference to the drawings are merely
15 illustrative of the technical solutions of the present disclosure but are not to be construed as limited to the technical solutions of the present disclosure.

[0037] The terms and words used in the following description and claims are not limited to the bibliographical meanings but are merely used by the inventor to enable a clear and consistent understanding of the invention. Accordingly, it should be
20 apparent to those skilled in the art that the following description of the present invention is provided for illustration purposes only and not for the purpose of limiting the invention as defined by the appended claims. As used in the description of the invention and the appended claims, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise.

25 [0038] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure pertains. It will be further understood that terms, such

as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

- 5 [0039] The present invention introduces a series of groundbreaking embodiments designed to autonomous grasping of non-cooperative spacecraft using the novel Grasping and Preloading Mechanism (GPM).

[0040] In the primary embodiment, the present invention discloses a novel Grasping and Preloading Mechanism (GPM) for Indian On-Orbit Servicing (OOS) of existing
10 non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space. This is achieved by functionally integrating three essential mechanisms in the GPM of the servicer spacecraft: the robotic arm, the gripper mechanism, and the preloading mechanism. The robotic arm is used for identifying the client spacecraft within the grasp envelope and actuated to
15 grasp the LAR of the client spacecraft and pull it towards the preloading surface of the servicer spacecraft. The gripper mechanism is equipped with grasp fingers and preload fingers, which instantaneously grasp the LAR and arrest all DOF of the client spacecraft. The preloading mechanism with two stanchion grippers mounted at 120° angles to each other and 120° to the robotic arm gripper, ensuring balanced grasping
20 around the LAR and achieving the predefined preload between the spacecraft. Once the predefined preload reached the force sensor in the preloading surface cuts off the motion of the robotic arm. These mechanisms collectively ensure the autonomous grasping of non-cooperative spacecraft that have no special docking features.

[0041] In another embodiment, the present invention focuses on autonomous grasping
25 of non-cooperative spacecraft using the novel Grasping and Preloading Mechanism (GPM) in both GEO (1194 mm LAR) and LEO (937 mm LAR) types of spacecraft interface rings.

[0042] In yet another embodiment, the present invention is equipped with deck camera on the servicer spacecraft base and MES sensors on the robotic to monitor the servicer spacecraft to recognize the orientation of the client spacecraft before grasping and monitor the grasping orientation of the servicer spacecraft with the client spacecraft during and after the grasping. It ensures a safe distance grasping of LAR of client spacecraft through the servicer spacecraft.

[0043] In yet another embodiment of the present invention, the GPM is equipped with grasp fingers kept held down (stowed configuration) during launch by an ingenious wedge-type stopper and released once in orbit to perform the necessary operations efficiently, resulting in compact storage. The wedge-type stoppers are designed to avoid the need for an additional hold-down system, thereby reducing mass, launch costs, and enhancing overall system reliability. Moreover, the wedge-type stoppers in the stanchion gripper perform both the grasping and release functions of the client spacecraft with the servicer spacecraft using a single actuator.

[0044] In yet another embodiment of the present invention, the GPM is equipped with a robotic arm featuring a gripping mechanism with 6 degrees of freedom (DOF), allowing the servicer spacecraft to access the client spacecraft within the grasping envelope and initiate soft grasping using the grasp fingers, followed by grasping and alignment using the preload fingers. This combination of grasping and alignment ensures that the client spacecraft remains securely grasped to the servicer spacecraft by arresting all DOF of the client's LAR, preventing separation.

[0045] In yet another embodiment of the present invention, the GPM is equipped with an ingenious gripper mechanism, where the grasp fingers are profiled in such a way that they can positively grasp the LAR and prevent the client spacecraft from rebounding after the initial impact.

[0046] In yet another embodiment of the present invention, the GPM is equipped with a preload mechanism where stanchion grippers with force sensors are used to ensure

the predefined preload between the spacecraft and autonomously cut off the robotic arm movement once the predefined preload is reached. The structural arrangement of the two stanchion grippers and the robotic arm gripper, when the spacecraft are at the predefined preload stage, is designed so that all three grippers are separated by 120°
5 each, thereby ensuring balanced and uniform grasping around the LAR of the client spacecraft. This ensures the proper parallel orientation of the client spacecraft onto the servicer spacecraft, thereby initiating the On-Orbit Servicing (OOS) of existing non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space. Additionally, the GPM can push the client
10 spacecraft away from the servicer spacecraft after completing the OOS and release the client spacecraft, eliminating the need for a separate release mechanism. Thus, the GPM can autonomously grasp, preload, and release the client spacecraft repeatedly as required.

[0047] In yet another embodiment of the present invention, the GPM is featured with
15 a lightweight design under 2 kg, offering high precision with misalignment capabilities of ± 20 mm and $\pm 5^\circ$ across all axes, and can handle client spacecraft weighing up to 1.5 tons.

[0048] In yet another embodiment of the present invention, the GPM is featured with a closed-loop system that achieves safe-distance grasping and the desired preload
20 between spacecraft, monitored via a force-based cutoff sensor and mechanism entry sensors.

[0049] Overall, these embodiments provide a novel Grasping and Preloading Mechanism (GPM) for On-Orbit Servicing (OOS) to extend the life of non-cooperative spacecraft nearing end-of-life. The GPM interfaces with the servicer spacecraft through
25 a combination of a robotic arm, a gripper mechanism, and a preloading mechanism. The robotic arm, equipped with grasp and preload finger assemblies, is capable of instantaneously grasping and preloading the LAR of the client spacecraft.

Subsequently, the client spacecraft is pulled towards the preloading port mounted on the servicer spacecraft using the robotic arm. This mechanism ensures efficient use of mass, power, and space, and can repeatedly grasp, preload, and release the client spacecraft as needed, enabling effective OOS operations.

- 5 [0050] With reference to Figures 1 – 12, the novel Grasping and Preloading Mechanism (100) according to the present invention comprising the robotic arm (120), the gripper mechanism (140), and the preloading mechanism (160).

[0051] With reference to Figures 3 and 4, the GPM (100), configured with the servicer spacecraft (101), has the ability to autonomously grasp and preload the non-cooperative
10 client spacecraft (102) to perform On-Orbit Servicing operations. This is achieved through the operational and structural integration of the robotic arm (120), the gripper mechanism (140), and the preloading mechanism (160). The robotic arm (120), with 6 degrees of freedom (DOF), is mounted on the servicer spacecraft (101) through the servicer spacecraft interface (126) and is actuated to grasp the LAR (105) of the client
15 spacecraft (102) and pull it towards the stanchions (161) of the servicer spacecraft (101). The gripper mechanism (140) is mounted on the robotic arm (120) at the arm interface (148) and initiates soft grasping using the grasp fingers (141), followed by grasping and alignment using the preload fingers (142). This ensures that the client spacecraft (102) remains securely attached to the servicer spacecraft (101) by arresting
20 all DOF of the LAR (105). The preloading mechanism (160) includes stanchions (161) with stanchion grippers (162) that apply preload and grasp the LAR (105) of the client spacecraft (102) using an ingenious wedge-type stopper (163). A force sensor (164) is used to ensure the predefined preload between the spacecraft and to autonomously cut off the robotic arm (120) movement once the predefined preload is reached.

- 25 [0052] With reference to Figures 4, the structural arrangement of the two stanchion grippers (162) and the robotic arm gripper (140), when the spacecraft (101, 102) are at the predefined preload stage, is designed so that all three grippers (162, 140) are

separated by 120° each, thereby ensuring balanced and uniform grasping around the LAR (105) of the client spacecraft (102). This ensures the proper parallel orientation of the client spacecraft (102) onto the servicer spacecraft (101), thereby initiating the On-Orbit Servicing (OOS) of existing non-cooperative spacecraft reaching end-of-life (EOL) for life extension with optimized resources such as mass, power, and space. After completing the OOS operations, the stanchion grippers (162) and gripper mechanism (140) are actuated to push the client spacecraft (102) away from the servicer spacecraft (101), eliminating the need for a separate release mechanism. Thus, the GPM (100) can autonomously grasp, preload, and release the client spacecraft (102) repeatedly as required.

[0053] Additionally, the GPM (100) is equipped with a deck camera (103) on the base of the servicer spacecraft (101) and MES sensors (104) on the robotic arm (120) to monitor the orientation of the client spacecraft (102) before grasping and to track the grasping orientation of the servicer spacecraft (101) with the client spacecraft (102) during and after the grasping. This system ensures safe distance grasping of the LAR (105) of the client spacecraft (102) by the servicer spacecraft (101).

[0054] With reference to Figure 5, the preloading surface in the stanchion grippers (162) is wide enough to grasp LARs (105) with diameters ranging from 937 mm to 1194 mm, allowing the GPM (100) to grasp and preload both the 1194 mm LAR (105A) and the 937 mm LAR (105B) types of spacecraft interface rings. Moreover, the GPM (100) can grasp and preload any LAR (105) within this range. For example, as illustrated in Figure 5, the GPM (100) securely grasps an LAR (105) with an outer diameter of 1214 mm and an inner diameter of 1131 mm.

[0055] With reference to Figures 6 and 7, the robotic arm (120) primarily comprises an arm-I (121) and an arm-II (122), which are kept folded during launch and released once in orbit. The gripper camera (125) on the robotic arm (120) provides the cue for initiating soft grasping in a non-contact manner. The robotic arm (120) is mounted on

the servicer spacecraft (101) through the servicer spacecraft interface (126). The servicer spacecraft interface (126) and arm-I (121) are connected via a shoulder joint (123), which provides rotational and revolute motion to the robotic arm (120) assembly. Arm-I (121) and arm-II (122) are connected by an elbow joint (124),
5 allowing revolute motion of arm-II (122) with the gripper mechanism (140). Arm-II (122) and the gripper mechanism (140) are connected by gripper joints (149), which provide rotational motion to the gripper mechanism (140) in all three axes. This configuration gives the robotic arm (120) a gripping mechanism (140) with 6 degrees of freedom (DOF), enabling the servicer spacecraft (101) to access the client spacecraft
10 (102) within the grasping envelope and initiate grasping. Once the gripper mechanism (140) grasps the LAR (105) of the client spacecraft (102), the elbow joint (124) in the robotic arm (120) actuates to pull the client spacecraft (102) towards the stanchions (161) mounted on the servicer spacecraft (101).

[0056] With reference to Figures 8 and 9, the gripper mechanism (140) is rigidly
15 mounted at the end of the gripper joints (149) using the arm interface (148). The gripper mechanism (140) primarily comprises at least three grasp fingers (141) mounted on the finger housing (144) and preload fingers (142) mounted on the gripper housing (145) to initiate soft grasping using the grasp fingers (141), followed by grasping and alignment using the preload fingers (142). The grasp motor (146) is used to actuate the
20 grasp fingers (141) against the compression springs (143), while the preload motor (147) actuates the preload fingers (142). The grasp fingers (141) move outward against the compression springs (143) and inward with the assistance of the compression springs (143). The MES sensor (104) in the gripper mechanism (140) is used to measure the separation distance between the grasp fingers (141) and sends an
25 autonomous signal to the grasp motor (146) and preload motor (147) for a specific duration of actuation. The contact switch (150) in the gripper mechanism (140) is used to stop the grasp motor (146) and preload motor (147) when the required preload is

achieved between the preload fingers (142) and the LAR (105) surface, ensuring the secure grasping of the client spacecraft (102) by arresting all degrees of freedom.

[0057] With reference to Figure 8, the grasp fingers (141) are profiled in such a way that they can positively grasp the LAR (105) and prevent the client spacecraft (102) from rebounding after the initial impact. Also, the grasp fingers (141) kept held down (stowed configuration) during launch by an ingenious wedge-type stopper (163) and released once in orbit to perform the necessary operations efficiently, resulting in compact storage. The wedge-type stoppers (163) are designed to avoid the need for an additional hold-down system, thereby reducing mass, launch costs, and enhancing overall system reliability.

[0058] Additionally, when the deck camera (103) identifies the client spacecraft (102) within the grasping envelope, it actuates the robotic arm (120) with the gripper assembly (140) to initiate the grasping of the LAR (105). The orientation of the gripper assembly (140) is monitored through the gripper camera (125), which guides the positioning of the gripper assembly (140) to align the LAR (105) between the grasp fingers (141). Simultaneously, the grasp motor (146) is actuated to move the grasp fingers (141) outwards against the force of the compression springs (143) to facilitate the alignment of the LAR (105) between the grasp fingers (141). The separation distance between the grasp fingers (141) is measured by the MES sensors (104). When this distance exceeds 20 mm, the finger housing (144) is released, allowing the grasp fingers (141) to move inwards with the assistance of the compression springs (143) and initiate the soft grasping of the LAR (105). Next, the preload motor (147) actuates the preload finger (142) to move upwards, bringing the top surface of the preload finger (142) into contact with the LAR (105) surface. The contact switch (150) mounted on the preload finger (142) measures the preload between the preload finger (142) and the LAR (105) surface. Once the predefined preload is reached, a signal is sent to the preload motor (147) to stop, and the grasp motor (146) is actuated in the opposite direction to achieve rigid grasping by the grasp fingers (141). This process ensures that

the LAR (105) of the client spacecraft (102) is securely grasped between the grasp fingers (141) and preload fingers (142), fully arresting all degrees of freedom (DOF) of the client spacecraft (102) and ensuring proper alignment between the spacecrafts.

[0059] With reference to Figure 10, the preloading mechanism (160) comprises the stanchion grippers (162) equipped with wedge-type stoppers (163) on the stanchions (162). These stanchion grippers (162) are enabled with force sensors (164) to monitor the preload when the client spacecraft (102) contacts the wedge-type stoppers (163) of the stanchion grippers (162). Once the predefined preload is achieved, the force sensors (164) signal the actuator to stop the motion of the robotic arm (120), ensuring the proper parallel orientation of the client spacecraft (102) onto the servicer spacecraft (101) for initiating the On-Orbit Servicing (OOS) operations. Moreover, the wedge-type stoppers (163) in the stanchion grippers (162) perform both the grasping and release functions of the client spacecraft (102) with the servicer spacecraft (101) using a single actuator.

[0060] With reference to Figures 11 and 12, demonstrations of the validation and lab-level testing of the Grasping and Preloading Mechanism (GPM) (100) prototype and hardware are shown. Conceptually, it is evident that the GPM (100) features a lightweight design of under 2 kg, offering high precision with misalignment capabilities of ± 20 mm and $\pm 5^\circ$ across all axes, and can handle client spacecraft (102) weighing up to 1.5 tons. Additionally, the GPM (100) includes a closed-loop system that ensures safe-distance grasping and achieves the desired preload between spacecraft, monitored via a force sensor (164) and MES sensors (104).

[0061] With reference to Figure 13, the method for the autonomous grasping of non-cooperative spacecraft using the GPM (100) involves two key phases.

[0062] In the initial grasping phase, the deck camera (103) is used to identify the orientation of the client spacecraft (102) and determine that both spacecraft are within the grasping envelope, preparing the servicer spacecraft (101) for grasping. The GPM

(100) actuates the robotic arm (120) with the gripper assembly (140) to initiate the grasping of the LAR (105). The orientation of the gripper assembly (140) is monitored by the gripper camera (125), which guides the positioning of the gripper assembly (140) to align the LAR (105) between the grasp fingers (141).

- 5 [0063] The grasping process by the gripper mechanism (140) occurs in three stages:

Stage 1: The grasp fingers (141) move outwards through the actuation of the grasp motor (146), preparing them for grasping.

10 Stage 2: When the MES sensor (104) detects that the separation distance between the grasp fingers (141) exceeds 20 mm, the drive is cut off. The grasp fingers (141) then move inwards with the assistance of compression springs (143), achieving a soft grasp of the LAR (105).

15 Stage 3: The preload finger (142) moves upwards to align the LAR (105) between the grasp fingers (141) and the preload fingers (142). This sequence ensures a secure grasp, constraining all degrees of freedom (DOF) of the LAR (105) of the client spacecraft (102).

20 [0064] Once a secure grasp is achieved, the robotic arm (120) is actuated to pull the client spacecraft (102) towards the stanchion gripper (162) mounted on the servicer spacecraft (101) during the final preloading phase. In this phase, the desired preload between the spacecraft is ensured, and the force sensors (164) signal the actuator to stop the motion of the robotic arm (120), initiating the On-Orbit Servicing (OOS) operations.

25 [0065] After completing the OOS operations, the stanchion grippers (162) and gripper mechanism (140) are actuated to push the client spacecraft (102) away from the servicer spacecraft (101), thereby eliminating the need for a separate release mechanism. Consequently, the GPM (100) can autonomously grasp, preload, and release the client spacecraft (102) as needed, repeating the process as required.

[0066] The basic idea of the present invention is to provide a novel Grasping and Preloading Mechanism (100) for On-Orbit Servicing to extend the life of non-cooperative spacecraft nearing end-of-life. The GPM (100), integrated into a servicer spacecraft (101), comprises the robotic arm (120), the gripper mechanism (140), and the preloading mechanism (160). The robotic arm (120), equipped with grasp finger (141) and preload finger (142) assemblies, is capable of autonomously grasping the LAR (105) of the client spacecraft (102). Subsequently, the client spacecraft (102) is pulled towards the preloading mechanism (160) mounted on the servicer spacecraft (101) using the robotic arm (120). The mechanism ensures efficient use of mass, power, and space, and can repeatedly capture, preload, and release the client spacecraft (102) as required, enabling effective OOS operations.

[0067] The present invention may take many forms and modifications, and the specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms set forth in the detailed description, but rather to include all modifications and equivalents within the spirit and scope of the invention as defined.

We Claim

1. A grasping and preloading mechanism (100) for autonomous grasping and preloading of non-cooperative spacecraft, comprising:

5 a robotic arm (120) configured with 6 degrees of freedom mounted on a servicer spacecraft (101) for positioning and pulling a LAR (1105) of a client spacecraft (102);

10 wherein the 6 degrees of freedom include rotational and revolute motion provided by a shoulder joint (123), revolute motion provided by an elbow joint (124), and rotational motion in all three axes provided by a gripper joints (149);

a gripper mechanism (140) attached to the robotic arm (120) comprises a plurality of grasp fingers (141) and a preload finger (142), which are actuated by a grasp motor (146) and a preload motor (147), respectively, to grasp and constrain all degrees of freedom of the LAR (105) of the client spacecraft (102);

15 wherein the soft grasping is carried out using the grasp fingers (141), followed by secured grasping and alignment using the preload fingers (142);

20 a preloading mechanism (160) comprises a stanchion gripper (162) equipped with a wedge-type stoppers (163) and a force sensor (164) to ensure the predefined preload, and to send a signal to the actuator to stop the motion of the robotic arm (120), thereby initiating the OOS operations.

25 wherein the structural arrangement of the two stanchion grippers (162) and the robotic arm gripper (140), when the spacecraft (101, 102) are at the predefined preload stage, is designed so that all three grippers (162, 140) are separated by 120° each, thereby ensuring balanced and uniform grasping around the LAR (105) of the client spacecraft (102).

2. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the preloading surface in the stanchion grippers (162) is wide enough to grasp LAR (105) with diameters ranging from 937 mm to 1194 mm, allowing the GPM (100) to grasp and preload both the 1194 mm LAR (105A) and the 937 mm LAR (105B) types of spacecraft interface rings.
5
3. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the mechanism (100) is configured with a deck camera (103) to monitor the orientation of the client spacecraft (102) before grasping and to track the grasping orientation of the servicer spacecraft (101) with the client spacecraft (102) during and after the grasping, thereby ensuring safe distance grasping of the LAR (105).
10
4. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the wedge-type stoppers (163) in the stanchion grippers (162) perform both the grasping and release functions of the client spacecraft (102) with the servicer spacecraft (101) using a single actuator.
- 15 5. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the grasp fingers (141) are profiled in such a way that they can positively grasp the LAR (105) and prevent the client spacecraft (102) from rebounding after the initial impact.
6. The grasping and preloading mechanism (100) as claimed in claim 1, wherein a gripper camera (125) on the robotic arm (120) provides the cue for initiating soft grasping in a non-contact manner.
20
7. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the grasp fingers (141) kept held down (stowed configuration) during launch by the wedge-type stopper (163) and released once in orbit to perform the necessary operations efficiently, resulting in compact storage.
25

8. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the wedge-type stoppers (163) are designed to avoid the need for an additional hold-down system, thereby reducing mass, launch costs, and enhancing overall system reliability.
- 5 9. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the mechanism (100) features a lightweight design of under 2 kg, offering high precision with misalignment capabilities of ± 20 mm and $\pm 5^\circ$ across all axes, and can handle client spacecraft (102) weighing up to 1.5 tons.
- 10 10. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the mechanism (100) includes a closed-loop system that ensures safe-distance grasping and achieves the desired preload between spacecraft, monitored via a force sensor (164) and MES sensors (104).
11. A method for grasping and alignment achieved by the gripper mechanism (140), comprising the steps of:
 - 15 actuating the grasp motor (146) to move the grasp fingers (141) outward against the force of a compression springs (143) to facilitate the alignment of the LAR (105) between the grasp fingers (141);
 - measuring the separation distance between the grasp fingers (141) using MES sensors (104) and, when the separation distance exceeds 20 mm, releasing the
 - 20 finger housing (144) to allow the grasp fingers (141) to move inward with the assistance of the compression springs (143) to initiate soft grasping of the LAR (105);
 - actuating the preload motor (147) to move the preload finger (142) upward until the top surface of the preload finger (142) contacts the LAR (105) surface;
 - 25 measuring the preload between the preload finger (142) and the LAR (105) surface using a contact switch (150) mounted on the preload finger (142), and

sending a signal to the preload motor (147) to stop once the predefined preload is reached;

5 actuating the grasp motor (146) in the opposite direction to achieve rigid grasping by the grasp fingers (141), thereby securely grasping the LAR (105) of the client spacecraft (102) between the grasp fingers (141) and preload fingers (142).

ensuring that all degrees of freedom of the client spacecraft (102) are fully arrested, securing the alignment between the servicer spacecraft (101) and the client spacecraft (102).

10 12. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the mechanism (100) through the robotic arm (120) has able to pull the client spacecraft (102) parallel to the servicer spacecraft (101) stanchion grippers (162) located on the stanchions (161).

15 13. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the contact switch (150) in the gripper mechanism (140) is used to stop the grasp motor (146) and preload motor (147) when the required preload is achieved between the preload fingers (142) and the LAR (105) surface, ensuring the secure grasping of the client spacecraft (102) by arresting all degrees of freedom.

20 14. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the force sensor (164) is used to monitor the preload when the client spacecraft (102) butts onto the stanchion grippers (162) of the stanchions (161).

15. A method for the autonomous grasping and preloading of non-cooperative spacecraft using the grasping and preloading mechanism (100), comprising the steps of:

25 identifying the orientation of the client spacecraft (102) and confirming that the client spacecraft (102) and the servicer spacecraft (101) are within a grasping

envelope using the deck camera (103), thereby preparing the servicer spacecraft (101) for grasping;

actuating the robotic arm (120) with the gripper assembly (140) to initiate the grasping of the LAR (105) on the client spacecraft (102);

5 monitoring the orientation of the gripper assembly (140) using the gripper camera (125) to guide the positioning of the gripper assembly (140) such that the LAR (105) is aligned between a plurality of the grasp fingers (141);

executing the grasping and alignment process in the following stages:

10 actuating the grasp motor (146) to move the grasp fingers (141) outward, preparing them for grasping;

detecting, through the MES sensor (104), that the separation distance between the grasp fingers (141) exceeds 20 mm and cutting off the drive to the grasp fingers (141) to allow them to move inward with the assistance of compression springs (143), thereby achieving a soft grasp of the LAR (105);

15

actuating the preload finger (142) to move upward, aligning the LAR (105) between the grasp fingers (141) and the preload fingers (142), thereby grasping the LAR (105) and constraining all degrees of freedom of the client spacecraft (102);

20 pulling the client spacecraft (102) towards the stanchion gripper (162) mounted on the servicer spacecraft (101) by actuating the robotic arm (120);

ensuring the desired preload between the client spacecraft (102) and the servicer spacecraft (101) using force sensors (164), which signal the actuator to stop the motion of the robotic arm (120), thereby initiating the OOS operations.

25

16. The grasping and preloading mechanism (100) as claimed in claim 1, wherein after completing the OSS operations, the stanchion grippers (162) and gripper mechanism (140) are actuated to push the client spacecraft (102) away from the servicer spacecraft (101), eliminating the need for a separate release mechanism.
- 5 17. The grasping and preloading mechanism (100) as claimed in claim 1, wherein the mechanism (100) can autonomously grasp, preload, and release the client spacecraft (102) repeatedly as required.

Dated this 07th Day of August 2024

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ABSTRACT

A NOVEL GRASPING AND PRELOADING MECHANISM FOR GRASPING NON-COOPERATIVE SPACECRAFTS

5 The present invention is the development of a novel Grasping and Preloading
Mechanism (100) for On-Orbit Servicing to extend the life of non-cooperative
spacecraft nearing end-of-life. The GPM (100), integrated into a servicer spacecraft
(101), comprises the robotic arm (120), the gripper mechanism (140), and the
preloading mechanism (160). The robotic arm (120), equipped with grasp finger (141)
10 and preload finger (142) assemblies, is capable of autonomously grasping the LAR
(105) of the client spacecraft (102). Subsequently, the client spacecraft (102) is pulled
towards the preloading mechanism (160) mounted on the servicer spacecraft (101)
using the robotic arm (120). The mechanism ensures efficient use of mass, power, and
space, and can repeatedly capture, preload, and release the client spacecraft (102) as
15 required, enabling effective OOS operations.

Figure. 3.